IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 00.0000/ACCESS.0000.DOI

An Adaptive Distributed Averaging Integral Control Scheme for Micro-Grids with Renewable Intermittency and Varying Operating Cost

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ABSTRACT The increasing penetration of intermittent renewable energy resources in micro-grids poses several issues, such as stochastic power generation, demand and supply miss-match, frequency fluctuation, and economic dispatch problems. To address such critical issues, a distributed secondary control scheme based for micro-grids with varying operating cost and intermittent renewable energy resources is proposed for frequency regulation and economic load dispatch. The paper presents an adaptive distributed averaging integral control scheme with conditional uncertainties, namely varying operating costs, and renewable intermittency. The proposed control scheme adapts to the uncertainties by updating the control law parameters dynamically and can maintain overall network stability. The distributed control scheme employs communication channels for exchange of generation data from the neighboring power units for optimal power sharing and consensus among the power units. An additional controller at tertiary control layer of the hierarchical control architecture is also augmented in the control structure to economically dispatch the load and the consensus-based algorithm guarantees optimal load sharing. The proposed communication based control scheme reveals the best combination of performance and flexibility. A performance-based comparative analysis is also presented, validating the effectiveness of the proposed control scheme compared to the prior works. The robustness and performance of the proposed control scheme is illustrated through computer simulations.

INDEX TERMS Adaptive Control, Distributed Averaging based Integral, Economic Load Dispatch, Micro-Grids, Renewable Intermittency.

I. INTRODUCTION

MOTIVATED by the technological, economic and environmental aspects, the integration of renewable energy resources in power networks is increasing globally. Most of the renewable power units are connected to the system via alternating current inverters. As a consequence, the power generation structure is moving from large and centralized power plants to small and distributed power units. Since the physical structure of inverters and synchronous generators differ widely. A significant reduction in synchronous power generation occurs. Moreover, various issues such as frequency fluctuations, supply-demand mismatch, system instability, and economic load dispatch issues during peak and off-peak periods emerge due to the renewable intermittency [1], [2], [3], [4]. Hence, resulting in power system being operated under stressed conditions [5]. The stochastic nature, low inertia and lack of inherent synchronization capability of renewable energy resources are the reasons for the above mentioned issues. Therefore, new control strategies are essential to guarantee a reliable and efficient micro-grid operation. The growing complexities in terms of the active number of micro-grid elements and network dynamics render inflexible and centralized approaches inappropriate. Hence, creating a clear need for a robust and distributed solution [6].

Distributed Averaging-based Integral (DAI) algorithms rely on the averaging of integral actions that formulate ef-

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2019.2960855, IEEE Access

ficient solutions [7]. The major advantage of the distributed character of such kind of protocol is, no requirement of central computational entity [8]. The individual power units only exchange information with their respective neighboring nodes [9]. The most significant among several other control schemes in micro-grids is frequency control. The frequency control is further divided into three hierarchical layers i.e., primary-layer, secondary-layer and tertiary-layer control [10], [11]. In this paper, we have focused on secondary frequency control in the micro-grid system. The literature on secondary frequency DAI controllers is reviewed as follows.

Formerly in [12], [13], and [14], DAI algorithm was proposed to deal secondary frequency control in bulk power system. However, DAI for micro-grids with low and medium voltage levels were discussed in [9], [15], and [16] up to an excessive extent. The authors in [12] and [17] extended the research to accomplish asymptotically optimal injections and adaptation to the highly complex physical system model. As the closed-loop DAI controlled micro-grid is a cyber-physical system, its performance and stability significantly rely on neighbor communication. Regardless of the advancements, the communication-based controllers in bulk power systems undergo certain problems, for example, link failures, information loss, and communication delays [6], [18]. The reason behind such uncertainties are packet loss, packet sequence disturbance, congestion and quality of the communication channels. Thus, resulting in the reduction of overall performance or even in some cases affect the overall system stability. However, such uncertainties were not incorporated in DAI controlled micro-grid models.

The decentralized and distributed techniques are generally based on PI controllers in order to restore the voltage and the frequency of the power system [19]. For regulation purposes decentralized technique employs local measurements, however, distributed technique incorporates information gathered from neighboring Distributed Generating Units (DGUs), which requires a communication network and hence ultimately increasing the reliability and security in an isolated micro-grid [20]. Presently an algorithm based on consensus among the DGUs is added in the distributed approach for improving the power-sharing [21].

In micro-grids, the authors in [22] modeled communication delays with secondary frequency controllers in centralized Proportional Integrator (PI) cases. The authors in [23] proposed centralized PI with a model predictive controller and with a smith predictor. A small signal-analysis of a model was executed in the above-mentioned research works with constant delays. Moreover, a distributed control scheme for frequency regulation with plug and play capability and load variation was proposed in [24]. The authors in [1] discusses a power grid with intermittent renewable energy resources and propose a compound control strategy for frequency regulation using model predictive control and distributed leader-follower consensus control schemes. However, frequency control with DAI in a micro-grid with intermittent renewable energy resources was not considered.

Distributed control of micro-grids was proposed in [25], [26]. The authors elaborate a dynamic communication topology along with conditions for stability under time-varying delays. However, the above-mentioned works are limited to distributed control on the cyber layer and do not incorporate the physical layer. Moreover, the control schemes in the above research works were restricted to power-sharing approaches, while secondary frequency control was not well-thought-out. Although, in [27], secondary frequency control in micro-grids with constant and fast varying delays on the cyber-physical layer was investigated in detail. However, renewable intermittency was not modeled in the above works.

The optimal operating cost is a tertiary control level task and is achieved by solving an Economic Load Dispatch (ELD) optimization problem. This type of controller is often expressed under a centralized approach and requires a considerably high amount of time to solve an optimization problem. Although, in micro-grids, uncertainties can occur at a significantly less time. Therefore, the optimal dispatch is not updated for this time scale. In order to solve the optimal dispatch at relatively small intervals, decentralized or distributed approaches are employed. Adaptive droop control is the most common approach used to attain optimal operation cost based on decentralized schemes [28]. In this scheme, the distributed controllers at each DGU are tuned according to their respective operating costs. However, as the DGUs do not share operating cost information, the global minimum operating cost is not accomplished. The authors in [29] investigates an ELD problem in a smart grid with communication uncertainties. The authors discusses a new kind of distributed dispatch algorithm to achieve optimal dispatch of electrical power by sharing load among the DGUs, while guaranteeing consensus among incremental cost (IC) using weighted communication links among the neighboring DGUs.

Various techniques used for optimal operating cost based on a distributed control approach are as follows: gradient consensus and incremental cost consensus (ICC) are discussed in [30] and [31]. The ICC is employed in Multi-Agent System (MAS) and is based on IC and consensus algorithm. Global supply-demand mismatch and IC are assessed for each DGU in [32], however, the formerly mentioned research works do not consider the generating power limits. Although, the authors in [31] and [33] used external controllers, in order to consider the power generating limits while applying the ICC approach. In such cases, a pseudo operating cost for neighboring DGUs is estimated. Unlike ICC, the distributed gradient approach computes the incremental cost [30], [34]. All these research works include the IC as the consensus variable. However, the variable operating cost of power units with respect to time was not incorporated in DAI controlled micro-grids. Moreover, due to the renewable intermittency, adaptation techniques for DAI control scheme are essential to update the control law parameters and is still an open research area [35].

The paper presents an adaptive DAI controlled micro-grid

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with a variable operating cost of power units and renewable intermittency. Such disturbances are subjected to the model network at several time intervals to present the effectiveness and adaptability of the proposed controller. As the operating cost of the DGUs vary with time, a centralized ELD algorithm is also considered in the control structure. The area power balance is maintained by communication channels for power-sharing and network stability. The communication channels are used only to transmit generation data of the neighboring DGUs and have no physical relationship with the power lines. The generation data transmitted via the communication lines are provided to the distributed controllers to manage the area power balance and economic dispatch. In the present scenario, we considered an ideal communication network without any delays and information loss. Moreover, to handle renewable intermittency, adaptive control techniques are employed in the control structure. The micro-grid is composed of five DGUs and two constant load areas. The power units DGU1, DGU2, and DGU3 are conventional synchronous generators while the power units DGU4 and DGU5 are renewable energy resources. The major contributions of the present research work are:

- A secondary frequency adaptive DAI control scheme for micro-grids is modeled to overcome the varying operating cost and renewable intermittency uncertainties.
- To address the fluctuating operating cost of the DGUs, an ELD optimization algorithm is integrated within the control structure to meet the load demand economically.
- Renewable intermittence results in a) power generation loss, b) network imbalance, c) a change in network topology and d) system instability. Therefore, renewable intermittency is incorporated into the micro-grid model to evaluate the robustness of our proposed solution.

The rest of the paper is organized as follows: In Section 2, we describe some preliminaries of Algebraic-Graph Theory, the micro-grid model, and ELD algorithm. Section 3 explains the DAI control scheme. Various Adaptive techniques are also presented in this Section. Furthermore, the performance analysis is validated in Section 4 with the comparison of adaptive schemes for DAI using the MATLAB based model. Section 5 concludes the paper with a brief conclusion and future work.

II. INITIATIONS

A. NOTATIONS

Let $\Re$ defines set of real numbers and the notations $\Re_{\geq 0}$, represents a set $\{x|x \in \Re|x \geq 0\}$, while $\Re_{>0}$ denotes the set $\{x|x \in \Re|x > 0\}$, also $\Re_{<0}$ denotes the set $\{x|x \in \Re|x < 0\}$. Let $|z|$ be a set such that $|z|$ symbolizes the cardinality of $|z|$ and $|z|^s$ indicates the set of all the subsets of the set $|z|$ comprising of s elements. Let O_m denotes the null vector, 1_m denotes a vector of all elements to be 1, I_m is an identity matrix and $O_{m\times m}$ is a matrix with all zero elements of the order $m \times m$, $x = col\left(x_i\right) \in \Re$ represents a vector with entries x_i, for $i = \{1, ..., m\}$. A matrix $diag\left(a_c\right)$ with diagonal elements equal to $a_c \in \Re_{\geq 0}$ and rest of the entries are equal to zero. For $A \in \Re^{m\times m}$ such that $A > 0$ meaning A is a symmetric positive definite matrix.

B. GRAPH THEORY

Let g denote a graph which is undirected and $g = (U, S)$, where, $U = \{1, ..., m\}$ signifies the set of units or nodes and $S \subseteq [U]^2$, where $S = \{s_1, ..., s_m\}$denotes the set of undirected edges of g. In the context of current work, every node represents a power generating unit or power unit. Also, $\mathcal{A} = \Re^{|M|\times|M|}$ represents the adjacency matrix of g, having elements $a_{ij} = a_{ji} = 1$ only if an edge exists between i and j, otherwise $a_{ij} = 0$. Moreover, $d_c = \sum_{j=1}^{|U|} a_{ij}$ defines the degree of i^{th} node. The Laplacian of g is denoted by $\mathcal{L} = \mathcal{D} - \mathcal{A}$, as $D = diag(d_c) \in \Re^{|M|\times|M|}$. The arrangement of the nodes is of the order such that a consecutive pair of nodes is linked by an edge in a sequence called a path. If $\forall(i, j) = [U]^2$, a path exists from i to j, the graph is believed to be connected. The $\mathcal{L}$ matrix, of g is positive semi-definite with a simple zero eigenvalue given that g is connected The corresponding right eigenvector to the simple zero eigenvalue is 1_m, i.e., $\mathcal{L}\, 1_m = O_m$ [36].

C. MICRO-GRID MODEL

The power system considered in this research work is a micro-grid model consisting $m \geq 1$ DGUs or nodes [10], [37]. $U = \{1, ..., m\}$ represents set of DGUs/nodes. Under standard practice conditions, the following assumptions are made: the amplitudes of voltages $V_i \in \Re_{>0}$ of the nodes $i \in U$ are kept constant and the line impedance is assumed to be purely inductive [10]. θ_i is the phase angle of each node $i \in U : \Re_{\geq 0} \to \Re$ and its respective time derivative is indicated by $w_i = \frac{d}{dt}\,\theta_i$, representing the system's electrical frequency at the i^{th} node. The power network is assumed to be lossless, therefore no line losses are considered, i.e. any two nodes are connected via lossless line. The undirected graph g is considered connected, hence the power network is connected.

The micro-grid is composed of a heterogeneous generation pool containing synchronous generators as well as power electronics interfaced renewable energy power units. We have assumed that all the renewable energy DGUs are equipped with power measuring filters and droop control [38]. Hence, the power unit dynamics considered in this paper for i^{th} DGU, i.e. $i \in U$, can be described as:

$$w_i = \frac{d}{dt}\theta_i,$$
$$M_i \frac{d}{dt} w_i + D_i\left(w_i - w_{ref}\right) = {P_i}^r - G_{ii}{V_i}^2 + u_i - P_i, \tag{1}$$

where $M_i \in \Re_{>0}$ represents the coefficient of inertia, that in terms of power electronics interfaced renewable energy units can be denoted as $M_i = \tau_{p_i} D_i$, where $\tau_{p_i} \in \Re_{>0}$ is the low pass filter time constant of the power measurement filter [39]. Also $D_i \in \Re_{>0}$ denotes the coefficient of inverse droop or the damping, $w_{ref} \in \Re_{>0}$ represents the nominal or reference frequency of the micro-grid, $P_i{}^r \in \Re$ is the set-point of active power, $G_{ii}V_i{}^2 \in \Re_{>0}$ denotes the constant load at the i^{th} node. Moreover, $u_i : \Re_{>0} \rightarrow \Re$ denotes the control input of the system. All the parameters under standard practice are presumed to be represented in per unit system [10]. The real power flow $P_i : \Re^m \rightarrow \Re$ can be elaborated as considering loss less system,

$$P_i = \sum_{j \in u_i} V_i \, V_j \, sin \, (\theta_i - \theta_j), \tag{2}$$

where $\theta_{ij} = \theta_i - \theta_j$ for short-hand representation. The readers are referred to [40] for complete modeling of the micro-grid. For the sake of compact model illustration of the system, matrices are introduced for convenience i.e.

$$M = diag(M_i) \in \Re^{m \times m}, D = diag(D_i) \in \Re^{m \times m},$$

The vectors $u = col(u_i) \in \Re^m, P^T = col(P_i{}^r - G_{ii}V_i{}^2) \in \Re^m, w = col(w_i) \in \Re^m, \theta = col(\theta_i) \in \Re^m$. A potential function $F : \Re^m \rightarrow \Re$, is also introduced that is:

$$F(\theta) = -\sum_{\{i,j\} \in [U]^2} V_i V_j cos\,(\theta_{ij}),$$

Therefore, (1) can be written compactly as:

$$\begin{aligned} &\tfrac{d}{dt}\theta_i = w, \\ &M_i \tfrac{d}{dt} w_i + D_i\,(w_i - w_{ref}) = P^T + u - \nabla_\theta F(\theta), \end{aligned} \tag{3}$$

As we can observe the power flow symmetryP_i,

$$1_m^\top \nabla_\theta F(\theta) = 0. \tag{4}$$

D. ECONOMIC LOAD DISPATCH

An ELD optimization problem for a given system determines the optimal combination of power generated by each DGU, which curtails the overall operating cost of power units while meeting up with the load requirements and operational constraints. The micro-grid system under consideration consists of both conventional as well as renewable energy power units (i.e. wind and solar). The economic dispatch of power in such systems is quite different than the non-hybrid conventional thermal unit system [41], [42], [43]. The operating cost of the DGUs varies with time due to renewable intermittency, leading towards un-economical load dispatch which is highly undesired. The aim of the optimization algorithm augmented in the control structure is to maintain the varying operating cost of DGUs to an optimum level. According to [42] and [43] the quadratic equation below describes the operating cost of conventional thermal power units.

$$C_c(P_c) = \sum_{c=1}^{N} \gamma + \beta P_c + \alpha P_c^2, \tag{5}$$

where $C_c(P_c)$ is the operating cost of power generated by N number of conventional DGUs, P_c is the power generated by the conventional DGUs, while α, β, and γ are cost coefficients. Similarly, for renewable power units the operating cost can be described as,

$$C_r(P_r) = \sum_{r=1}^{H} P_r d_r, \tag{6}$$

where $C_r(P_r)$ represents the operating cost of H number of renewable DGUs, P_r is the power generated while d_r is the direct cost coefficient of renewable DGUs. Moreover, the total real power P_i is given as: $\sum_{i=1}^{m} P_i = \sum_{c=1}^{N} P_c + \sum_{r=1}^{H} P_r$, where $N \geq 1$ represents the number of conventional while $H \geq 1$ represents the number of renewable energy DGUs. Therefore, the model of ELD for the overall micro-grid can be written as:

$$\begin{aligned} &min. \sum_{c=1}^{N} C_c P_c + \sum_{r=1}^{H} C_r P_r \\ &subject\ \ to \\ &\sum_{c=1}^{N} P_c + \sum_{r=1}^{H} P_r = L^T \\ &P_c^{min} \leq P_c \leq P_c^{max} \\ &0 \leq P_r \leq P_r^{max} \end{aligned} \tag{7}$$

where $P_c{}^{min}$ and $P_c{}^{max}$ are the lower and upper bound of P_c respectively, while $P_r{}^{max}$ is the rated maximum power of renewable power units. The total demand is represented by L^T. The nominal operation of the generator's real power output is restricted to the bounds as described above [42], [43]. The cost values of all the generators obtained from the above optimization problem are then assigned to the positive definite matrix $\boldsymbol{B}$. The values of the matrix $\boldsymbol{B}$ are updated with respect to time. This scenario of updating cost represents that the DGUs operating cost is variable and differs for each interval of time due to renewable intermittence.

III. CONTROL SCHEME

A. DAI (FIXED CONTROL PARAMETERS)

The micro-grid under discussion works at or approximately at the nominal frequency w_{ref}. Though, inspecting the synchronous solution $(\overset{*}{w} = w_e 1_m)$, $\overset{*}{\theta}_{ij}$ a constant phase angle difference of the micro-grid in (3) and a constant control input $\overset{*}{u}$, we get

$$\begin{aligned} 0 = 1_m^\top \left\{ M \tfrac{d}{dt} w + D\,(w_e - w_{ref}) \right\} \\ = P^T + \overset{*}{u} - \nabla_\theta F(\theta), \end{aligned}$$

Comparing the above equation with (3), we have:

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$$w_e = w_{ref}\left[\frac{1_m^\top\left(P^T+\overset{*}{u}\right)}{1_m^\top D 1_m}\right], \tag{8}$$

Generally, $1_m^\top P^T \neq 0$ as the load $G_{ii}V_i^2$ is usually unknown. Thus, $w_e \neq w_{ref}$ which is the undesired result, unless and until an additional control input $\overset{*}{u}$ is introduced which cares for power imbalance. The control structure results in $\overset{*}{u}$, $w_e = w_{ref}$ and is termed as a secondary frequency control. Based on the research work of [12], [15], and [17], the secondary frequency control structure for the system in (3) is presented in (9) and is referred to as DAI control law,

$$\begin{aligned} &u = -p, \\ &\tfrac{d}{dt}p = X\left(w - 1_m w_{ref}\right) - k_c B\mathcal{L}Bp. \\ &\tfrac{d}{dt}p = Xe - Y \end{aligned} \tag{9}$$

where $X, k_c \in \Re^{m\times m}$ are diagonal gain matrices with all non-negative entries on the diagonal. Also, $e = (w - 1_m w_{ref}), Y = k_c\ B\ \mathcal{L}\ Bp$, and $\mathcal{L} = \mathcal{L}^T \in \Re^{m\times m}$ is the Laplacian matrix of the connected graph g, which is the communication channel for the power units to communicate with the neighboring nodes. The positive definite matrix ***B***, consisting elements $B_{ii} > 0$ is the cost coefficient for node i of secondary controller. The authors in [12], [15], [17], proved that the control law mentioned earlier in (9) is an appropriate secondary frequency control structure of the proposed micro-grid. Thus, $w_e = w_{ref}$ can be achieved by the control law, regardless of the unknown constant loads [13], [14]. The control law makes sure that power injected by the DGUs satisfy the identical peripheral cost constraint in the steady-state, i.e.

$$B_{ii}\,\overset{*}{u}_i = B_{jj}\,\overset{*}{u}_j \qquad \forall i,j \in U \tag{10}$$

where B_{ii} and B_{jj} are the respective diagonal elements of the B. By combining (3) and (9) the resulting nominal closed-loop system becomes:

$$\begin{aligned} &\tfrac{d}{dt}\theta = w, \\ &M\tfrac{d}{dt}w + D_i e = P^T - \nabla_\theta F(\theta) - p, \\ &\tfrac{d}{dt}p = Xe - Y \end{aligned} \tag{11}$$

For convenience and simplicity, the notion below is introduced to formalize our desired objective.

Def 1. (Synchronized motion): The micro-grid described in (11), exhibits a synchronized motion if and only if a solution of the form $(\forall t \geq 0)$ exists.

$$\overset{*}{\theta}(t) = \overset{*}{\theta}_\circ + \overset{*}{w}\,t,$$

$$\overset{*}{w} = w_e 1_m,$$

where $\overset{*}{\theta}_\circ \in \Re^m$ and $\overset{*}{w} \in \Re$. Therefore,

$$\left|\overset{*}{\theta}_{\circ,i} - \overset{*}{\theta}_{\circ,j}\right| < \tfrac{\pi}{2} \forall i \in U, j \in U_i.$$

The system in (11), has at least one synchronized motion *col* $\left(\overset{*}{w}, \overset{*}{p}, \overset{*}{\theta}\right)$ as explained in [12]. The identical marginal cost requirement in (10) is met due to such synchronized motion and is given by:

$$\overset{*}{p} \;=\; \alpha\, B^{-1}\, 1_m \tag{12}$$

$$\alpha = \left[\frac{1_m^\top P^T}{1_m^\top B^{-1} 1_m}\right] \tag{13}$$

Hence, $w_e = w_{ref}$ the control input $\overset{*}{u} = -p$ is acquired.

B. ADAPTIVE DAI

The DAI control scheme is made adaptive by incorporating certain techniques to update the control law during the occurrence of uncertainties. The need of adaptive control arose when we considered renewable intermittency in the proposed micro-grid. The traditional DAI with fixed control parameters resulted in a frequency consensus among the DGUs below or above the nominal value. Therefore, DAI could not cope with the uncertainties and the update of control parameters is essential. The function of the adaptive control scheme is to maintain stability and enhance the performance of the existing control law. The parameters of the adaptive control are not fixed, but rather vary with time searching for optimal configuration. Various states of the art adaptive techniques are discussed as follows:

1) Adaptive PI based DAI

Adaptive Proportional Integral or API controller is composed of time-varying parameters as compared to the classical PI controller. Recently, an adaptive technique has been applied to PI controllers due to their non-complex architecture, by counting in additional adaptive parameters to extend the limits of such controller. The foremost property of the adaptive PI controller is that the parameters are not constant but vary with time seeking for optimal configuration. The general update law for controller parameters is described as:

$$\overline{X} = k_p e(t) + k_i \int_0^t e(t)\,dt, \tag{14}$$

In the current scenario, the adaptive PI parameter update scheme for DAI control law can be written as:

$$\begin{aligned} \overline{X} = &\left[\left\{k_p - \gamma e \textstyle\int e^2(t)\,dt\right\}\right] + \\ &\left[k_i - \left[\textstyle\int\left\{(\gamma e(t))\left(\int e(t)dt\right)\right\}dt\left\{\int e(t)dt\right\}\right]\right], \end{aligned} \tag{15}$$

where γ is the learning rate, e is the error, $\overline{X}$, is the update parameter, k_p, k_i are the proportional and integral gains respectively of the adaptive PI-based DAI controller. Therefore, the control law in (9) will become:

$$\frac{d}{dt}p = \overline{X}e - Y. \tag{16}$$

The updated adaptive PI based DAI control law is presented in (16). The adaptive distributed control scheme ensures that each DGU operates at the nominal/reference frequency to maintain synchronization while keeping optimal power sharing by making consensus among the DGUs in the micro-grid.

Assumption I: Let us assume that the system in (11) as:

$$M\frac{d}{dt}w_{ref} + Dw_{ref} = P^T + X_\circ u_c - P_i, \tag{17}$$

After applying the updated control law $u = qu_c$, (17) can be written as:

$$M\frac{d}{dt}w + Dw = P^T + Xu - P_i. \tag{18}$$

We assume that $u = qu_c$, where u_c is the previous control input while u is the updated control input. On the other hand, $X_\circ$ is current gain value and X is the updated gain value. The error is defined as:

$$\widetilde{e} = \frac{d}{dt}w - \frac{d}{dt}w_{ref}, \tag{19}$$

Putting the values in (19) and taking derivative on both sides, we arrive with the following result.

$$\frac{d\widetilde{e}}{dt} = -\frac{D}{M}\left(w - w_{ref}\right) + \frac{1}{M}\left(Xu - X_\circ u_c\right), \tag{20}$$

However, at equilibrium point $\widetilde{e} = 0$ which implies $d\widetilde{e}/dt = 0$, so from the above equation we have:

$$q = X_\circ/X. \tag{21}$$

2) Lyapunov based Adaptive DAI

The proposition below offers an update of the control law in (9) by employing the Lyapunov function. Now consider the system in (11) with Assumption-I, the Lyapunov function denoted by V implies that:

$$V(\widetilde{e}, \theta) = \frac{\gamma}{2}\widetilde{e}^2 + \frac{X}{2}(q - q_\circ)^2, \tag{22}$$

where γ is the learning rate and $q_\circ$ is the current or old power angle. Solving (22) by taking derivative on both sides and substituting values from (17), (18), (20), and (21) we get:

$$\frac{dV}{dt} = -\frac{\gamma D}{M}\widetilde{e}^2 + (Xq - q_\circ)\left(\frac{dq}{dt} + \frac{\gamma\widetilde{e}}{M}u_c\right), \tag{23}$$

so if $dq/dt = -(\gamma\widetilde{e}/M)u_c$ then, $q = -\int(\gamma\widetilde{e}/M)u_c$. Consequently, by choosing such value of q, the Lyapunov function V for the system in (11), the control law in (9) is updated such that $\overline{\overline{X}} = -u_c.\int(\gamma\widetilde{e}/M)u_c$, such that $\overline{\overline{X}}$ is the update parameter of the DAI controller. Hence the control law in (9) becomes:

$$\frac{d}{dt}p = \overline{\overline{X}}e - Y. \tag{24}$$

3) MIT rule based Adaptive DAI

We have designed an adaptive control scheme for the DAI controlled micro-grid in (11) to with-stand the uncertainties occurring due to the intermittency of renewable power units. The methodology to design the adaptive control scheme is based on Model Reference Adaptive System (MRAS). MRAS generally employ MIT rule to curtail the error (difference) amongst the model reference value and the actual output value.

The following proposition for the system in (11) is made for the adaptation of the control law in (9) by employing MIT rule based on MRAS with Assumption I.

$$J(X) = \frac{1}{2}\widetilde{e}(X)^2, \tag{25}$$

Using (17), (18), (20) and taking the derivative of (25), we get:

$$\begin{aligned} \widetilde{X} &= -\gamma\widetilde{e}\left(\partial J/\partial X\right) = -\gamma\widetilde{e}\left(\partial\widetilde{e}/\partial X\right), \\ \widetilde{X} &= \gamma\widetilde{e}/M\int e. \end{aligned} \tag{26}$$

where $\widetilde{X}$ is the update parameter of the DAI controller. The resulting updated control law can be written as:

$$\frac{d}{dt}p = \widetilde{X}e - Y \tag{27}$$

Remark1 : According to Lyapunov Theorem, the adaptation techniques discussed above are asymptotically stable. The Lyapunov Theorem provides sufficient conditions for stability and the system's convergence [44].

IV. PERFORMANCE VALIDATION

In this paper, we have discussed a micro-grid with five DGUs, constant generating voltage and two constant loads. We have assumed that the transmission line admittances are purely inductive. In Figure 1, a single line diagram of the proposed micro-grid is presented. The DGU1, DGU2, and DGU3 are considered as synchronous generators, although, DGU4 and DGU5 are renewable power units. The closed-loop adaptive DAI control scheme for the discussed micro-grid is a cyber-physical system, where the performance and the stability significantly depend on neighbor communication. Regarding the network topologies, two possible cases are presented in

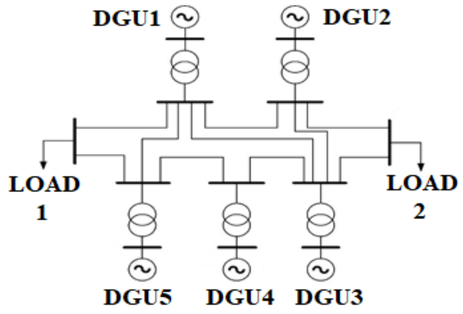

FIGURE 1. Proposed micro-grid electrical diagram

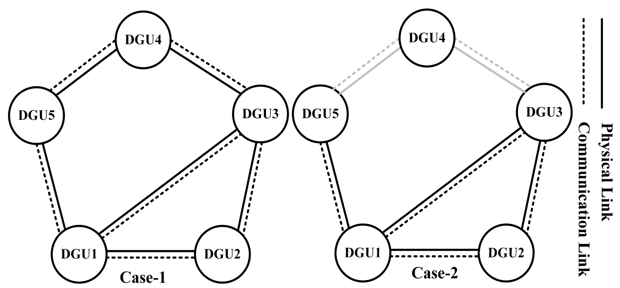

FIGURE 2. Proposed cyber-physical communication network

Figure 2 for convenience and simplicity. Other cases can also be investigated where one or more than one DGUs disconnect form the micro-grid network. The communication and power lines are isolated from each other and perform their sole purpose independently. There is no physical connection among the power lines and communication lines. In regards to the present work, we have considered an ideal communication network without information loss or any kind of delays. In case 1, the nominal topology is defined with all nodes connected, meeting the load demand. In case 2 as can be seen in Figure 2, the DGU4 disconnects from the network and no longer supports the rest of the DGUs in load sharing. The resulting effects on the micro-grid can be observed in the simulation results further discussed in this section. In Figure 3, the simulation result of micro-grid with the DAI control scheme (fixed control parameters) is presented. At Time T= 5 seconds, a variation in the load occurs which is marked as constant disturbance. Moreover, at T= 100 seconds, intermittence of renewable power units occurs and DGU4 exits the system while the remaining DGUs share the load. Furthermore, at T= 150 seconds, a change in operating cost of the DGUs can be observed. Note that in Figure 3, the DAI with fixed control parameters is unable to cope with the subjected disturbances. The frequency of the micro-grid deviates from the nominal value and makes an arbitrary consensus below the nominal value. Therefore, we have augmented Adaptive techniques discussed earlier in the control structure one by one in order to update the DAI control law.

The frequency response of DAI with constant control pa-

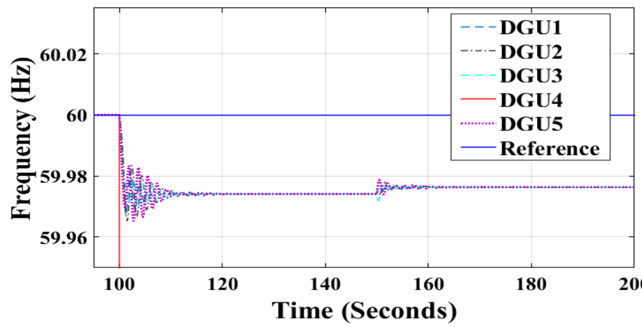

FIGURE 3. Frequency response to DAI (fixed parameters) control scheme

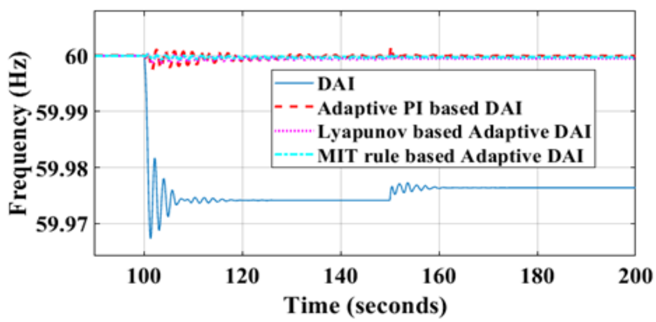

FIGURE 4. DGU1 frequency response to controllers

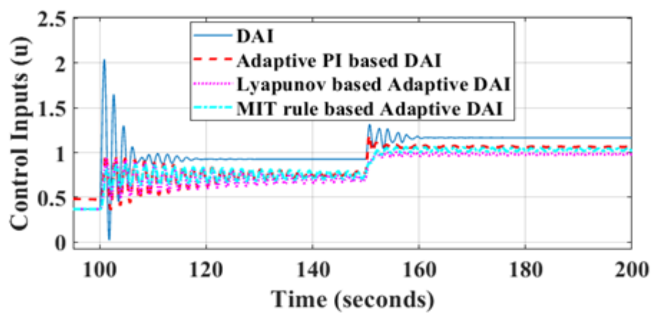

FIGURE 5. Control inputs to DGU1 from controllers

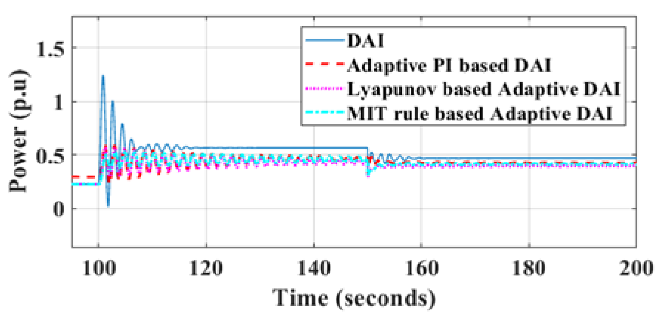

FIGURE 6. DGU1 marginal operating cost

TABLE 1. Performance indices of DGU 1 for Frequency

Performance Indices of Frequency/Adaptive Controller	DAI	API	MIT Rule based Adaptive control	LYAPUNOV based Adaptive control
ITEA	17920	22.9	182.8	359.4
IAE	60.2	0.8417	0.6336	12.92
ISE	9.045	0.34	0.00102	387.4
ITSE	2677	0.186	0.2846	106.6

Abbreviations:

API=Adaptive Proportional Integrator
DGU=Distributed Generating Unit
ITAE=Integral of Time Absolute Error
IAE=Integral of Absolute Magnitude of Error
ISE=Integral Square Error
ITSE=Integral Time Square Error

TABLE 2. Step Response of DGU1 Frequency

Controllers / Fields	RT	ST	S_{min}	S_{max}	OS	US	Peak	PT
DAI (fixed parameters)	100.624	154.605	59.967	59.981	0.0480	0	60.005	1.393
API	5.3355 e-09	2.3054	59.6649	600.0524	0.0874	0	60.0524	0.8780
Lyapunov based Adaptive Technique	0.01969	1.0072	50	60.0014	0.0032	0	60.0014	2.0483
MIT Rule based Adaptive Technique	7.0042	229.5625	59.9992	60.0002	0.0014	0	60.0006	5.1552

Abbreviations:

S_{max}: Settling max
ST: Settling Time
US: Undershoot
S_{min}: Settling min
RT: Rise Time
OS: Overshoot
PT: Peak Time

rameters and adaptive DAI techniques is presented in Figure 4. As evident from Figure 4, the adaptive DAI controllers managed to update the control law according to the disturbances subjected and were able to restore the frequency at nominal value as compared to DAI with constant parameters. The comparison of the controller's response shows that the adaptive DAI controllers perform far better than the DAI controller with constant parameters. The control inputs to the DGU1 from the aforementioned controllers are presented in Figure 5. Furthermore, the marginal operating cost of DGU1 with adaptive DAI controllers and DAI controller with constant parameters is shown in Figure 6. From the Figure, it can be observed that the ELD optimization problem minimizes the varying operating cost of the DGUs. Also, the adaptive controllers manage area power balance with respect to the operating costs of the DGUs. The results presented below are all considered for DGU1 for convenience. For the rest of the DGUs, the results can also be shown with various cyber-physical topologies.

Considering DGU1, the performance indices comparison of the above-discussed controllers are performed and recorded in Table 1. The values closer to zero elaborates the better performance. Note that the API is performing better in ITAE and ITSE analysis while MIT Rule performs better in IAE and ISE analysis. Almost all performance indices show that the adaptive DAI control scheme shows better performance as compared to DAI with constant control parameters. The step response characteristics of DGU1 such as rise time, settling time, overshoot, etc. are presented in Table 2. Observe that MIT Rule-based adaptive DAI control performs better than the API and Lyapunov based adaptive DAI control, and far better than DAI with constant control parameters. API seconds MIT Rule in performance but with fast rise time, settling time and peak time. Lyapunov based adaptive DAI control also shows better performance as can be visualized in Table 2.

The overall results presented above confirm the fact, that the system's trajectories converge to a synchronized motion if the control parameter values in Table 3 are summarized. The tuning of the DAI controller is discussed in [11]. The secondary frequency DAI controller performance is enhanced by augmenting the discussed adaptation techniques. The simulation results presented above show that for the investigated scenarios, our conditions are fairly conservative at equilibria

TABLE 3. Controller Tuning Parameters

DAI	Adaptive PI based DAI	Lyapunov based Adaptive DAI	MIT rule based Adaptive DAI
X=-500	X= -500	-	-
k_c=-200	k_c= -200	k_c= -200	k_c= -200
-	$\gamma = 0.4$	$\gamma = 9.6$	$\gamma = 284.4$

under highly stressed operating conditions.

V. CONCLUSION AND FUTURE WORK

The adaptive DAI controller is employed in the micro-grid system to handle the uncertainty of renewable intermittence. The adaptive DAI effectively handles the renewable intermittency and varying operating cost of the power units while keeping the system's frequency at nominal value. The use of adaptive DAI with ELD plays a pivotal role in economically addressing the varying operating cost of power units and thus, serving the load demand. The proposed micro-grid model demonstrates excellent performance with the employed control scheme. Future work may include the effect of power electronics devices on the power quality of the micro-grid, as well as the line losses that were assumed to be negligible. Further work may also include the robustness of the distributed controller for a micro-grid network with prosumer activities and how the proposed control scheme may be used to attain additional goals such as fault tolerance and harmonic compensation.

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This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2019.2960855, IEEE Access

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